

Review of Current FFAG Lattice Studies in North America

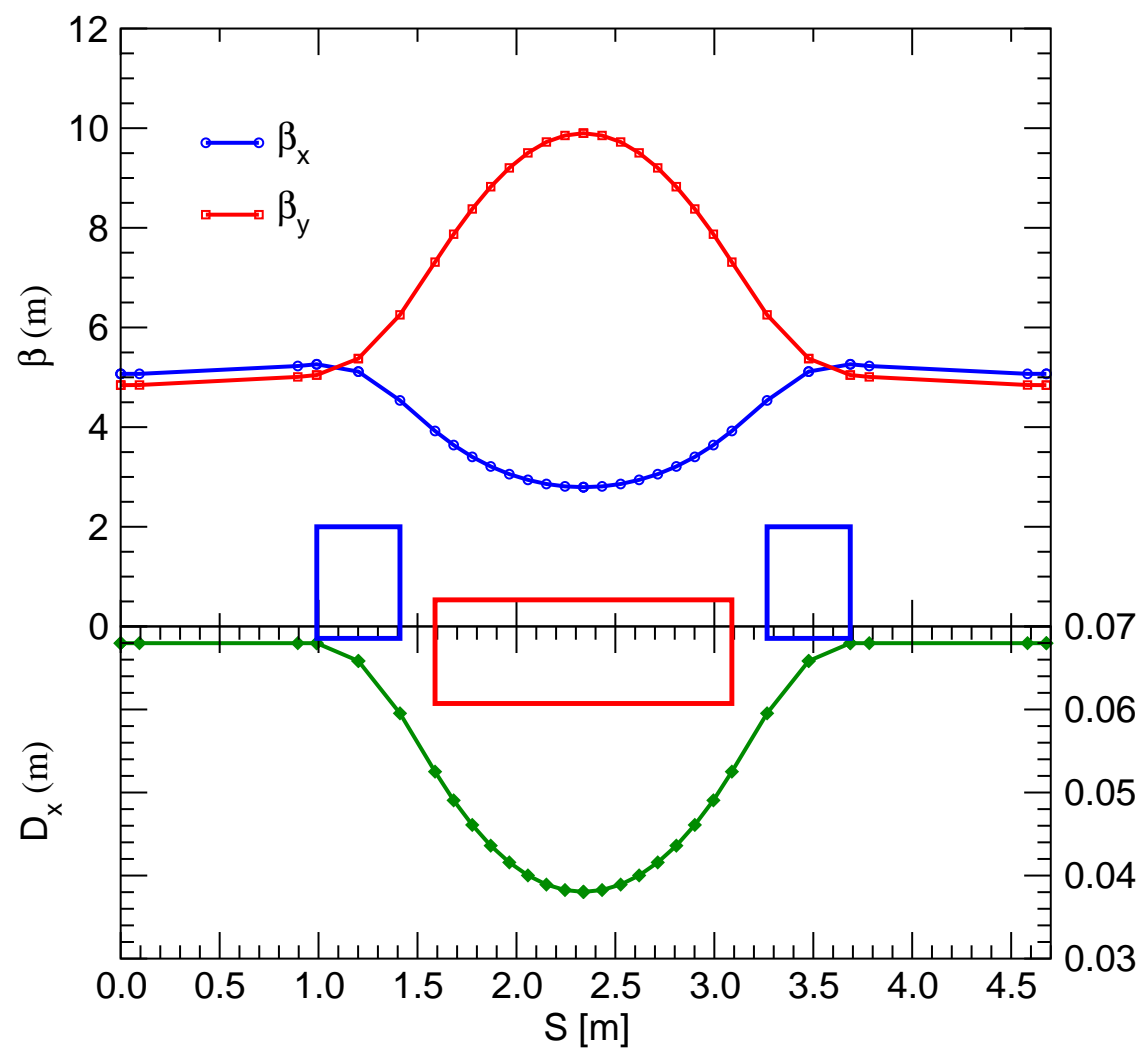
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- Introduction: non-scaling FFAGs
- New applications of non-scaling FFAGs
- Producing “optimized” linear non-scaling FFAG designs
- Analytic models for linear non-scaling FFAGs
- Tracking of non-scaling FFAGs
- Concluding remarks

- First FFAGs, and all FFAGs built thus far, are “scaling”
 - ◆ Transverse dynamics independent of energy, except for energy-dependent scaling factor
 - ◆ Tune is independent of energy: avoid resonances
 - ◆ Highly nonlinear magnets
- North American work has focused on “non-scaling FFAGs”
 - ◆ Most are “linear non-scaling FFAGs”: use magnets with a linear midplane field profile
 - ◆ Linear magnets thought to give larger dynamic aperture
 - ◆ Smaller physical magnet aperture
 - ◆ Tunes no longer constant: resonances
 - ★ Highly symmetric lattice (every cell the same, short cells) minimizes driving of multi-cell resonances
 - ★ Highly linear lattice minimizes driving of nonlinear resonances
 - ★ Rapid acceleration means little time spent on resonance

- General applicability
 - ◆ Magnet fields don't vary: allows rapid acceleration
 - ◆ Circular, so multiple passes through (expensive) RF
 - ◆ Often a good replacement for a linac
- Original motivation for recent interest in US/Canada: muon acceleration
 - ◆ Muons decay, so acceleration must be rapid
 - ◆ Linac prohibitively expensive, especially considering cost of 200 MHz RF required
 - ◆ Recirculating accelerator has problems
 - ★ Switchyard difficulty limits number of turns to 4–5
 - ★ This is still a lot of RF: expensive

- Electron-ion collider in the RHIC tunnel at BNL
- Accelerate polarized electrons as high as 10 GeV
- Avoid depolarizing resonances
- Baseline: recirculating linac
- Proposal (Trbojevic): replace with linear non-scaling FFAG
 - ◆ Accelerate from 3.2 GeV to 10 GeV
 - ◆ Accelerate rapidly through depolarizing resonances
 - ◆ Triplet (FDF) design, 273 cells



- AGS Upgrade being proposed
 - ◆ Upgrade to 1 MW beam power
 - ◆ Acceleration cycle must be shortened
 - ◆ Beam current must be increased
- One part of proposal: replace current 1.5 GeV booster with linac
 - ◆ Eliminate multiple ramp-ups required to fill AGS
- Alternative: use FFAG instead
 - ◆ Rapid acceleration, so doesn't increase cycle time substantially
 - ◆ Install small amount of RF: around 1000 turns to accelerate
 - ★ Prefer constant tune of scaling FFAG to avoid resonances
 - ◆ Need low magnetic fields to prevent H^- stripping: < 0.3 T
 - ★ Attempts to meet this field limitation with scaling FFAG failed

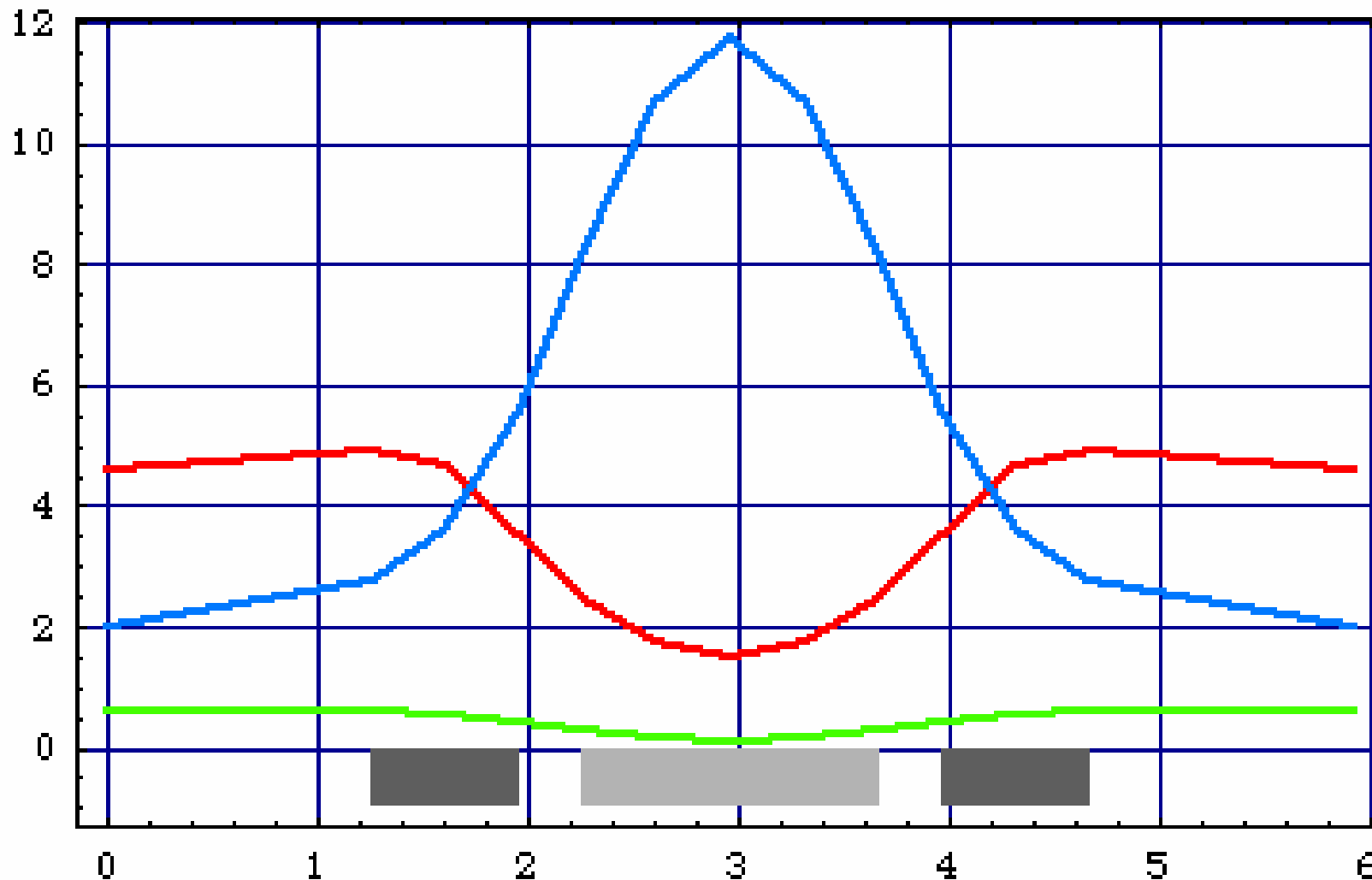
- Want non-scaling FFAG, but low chromaticity
- Consider equations of motion:

$$x'' + h^2(1 + n)x/(1 + \delta) = h\delta/(1 + \delta) \quad y'' + h^2ny/(1 + \delta) = 0$$

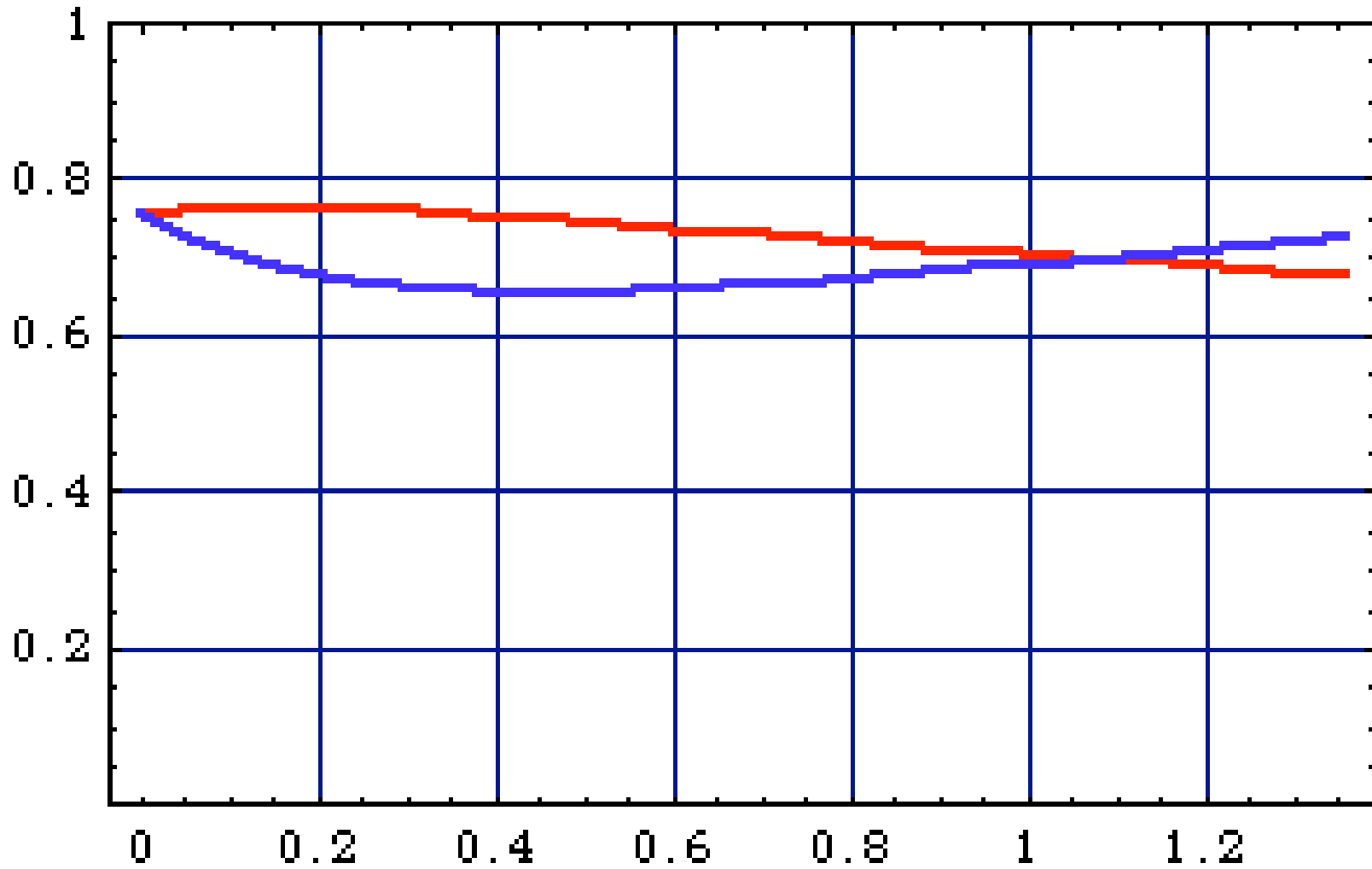
- ◆ If field index n is proportional to $1 + \delta$, vertical tune is independent of energy (Ruggiero)
- ◆ Horizontal tune not independent of energy, but close
- ◆ With end effects, both tunes become energy dependent, but effect is small
- Field index condition is local: field profile varies longitudinally along magnet
 - ◆ Solve for closed orbit and field self-consistently: Mathematica

Nonlinear Non-scaling FFAG: Lattice

β_H in m, β_V in m, 10x η in m vs. dist. in m

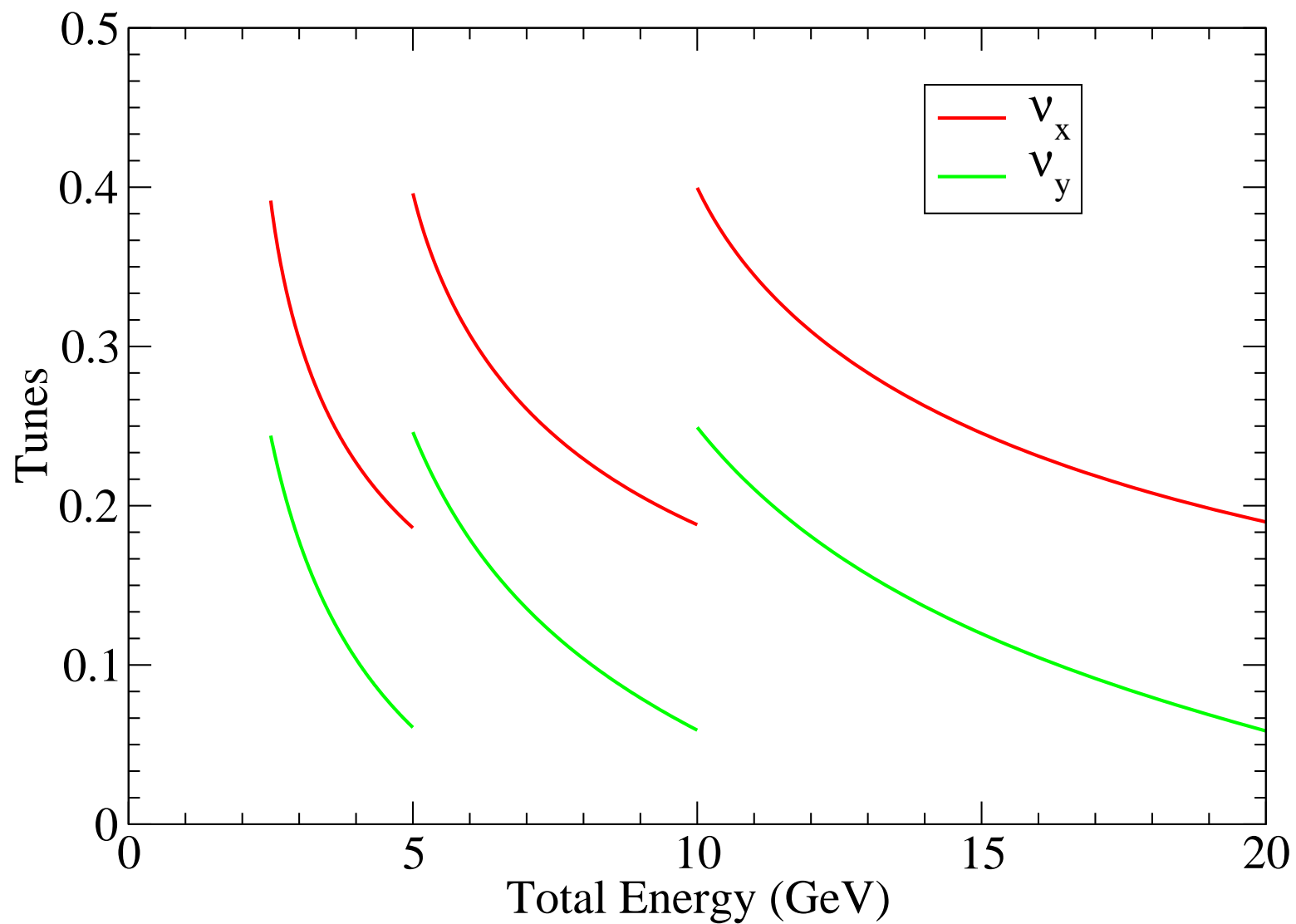


- Fractional tunes: integral parts are 39 and 37 (H/V)

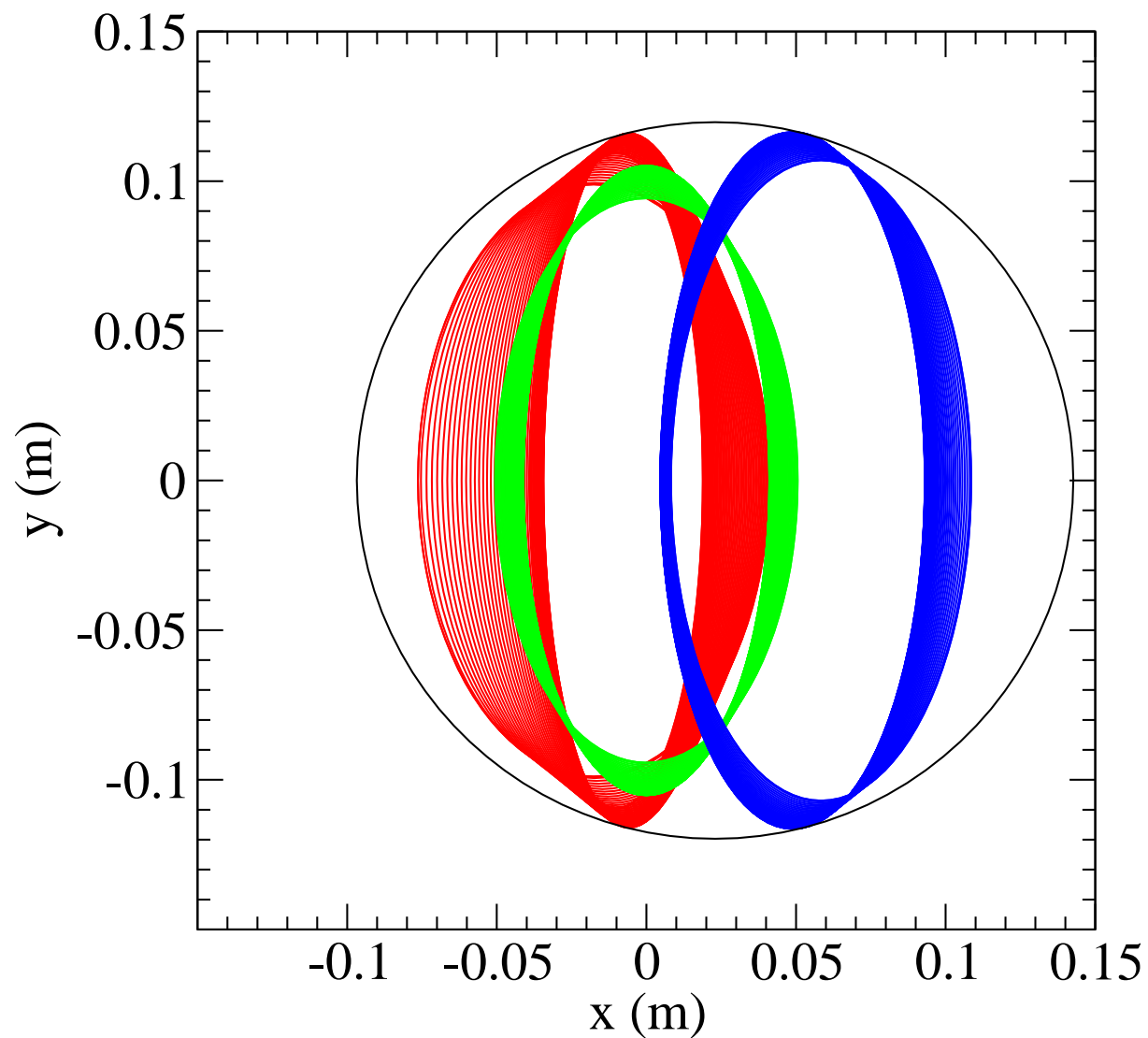


- Lattices are just simple repeated cells (doublet, triplet, FODO)
- Use optimizer to minimize some cost function to produce designs (Berg)
 - ◆ Cost function based on model for magnet and RF costs has been used (Palmer)
 - ◆ Decay cost has also been added, based on detector cost
- Much has been learned through this
 - ◆ Doublet cell is more cost-effective than triplet or FODO
 - ◆ Making the ring longer often reduces magnet costs (dispersion reduces aperture)
 - ◆ Optimal lattices has specific tune profiles, independent of central energy (fit in pipe)
 - ◆ Lower energy FFAGs cost more per GeV than higher energy
- Ability to find cost and parameters as a function of input parameters

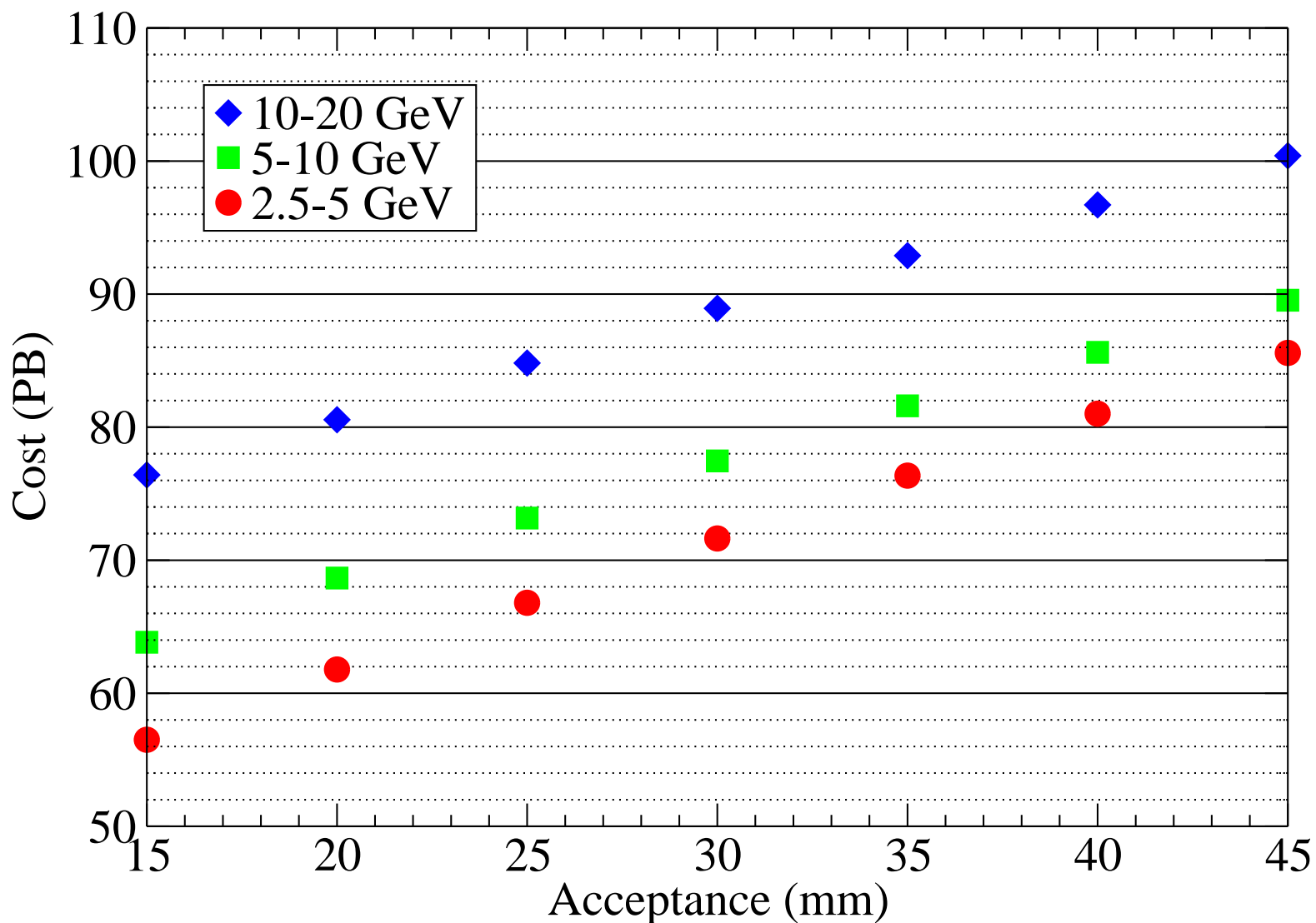
FFAG Tune Profiles



Ellipses in Magnet Aperture

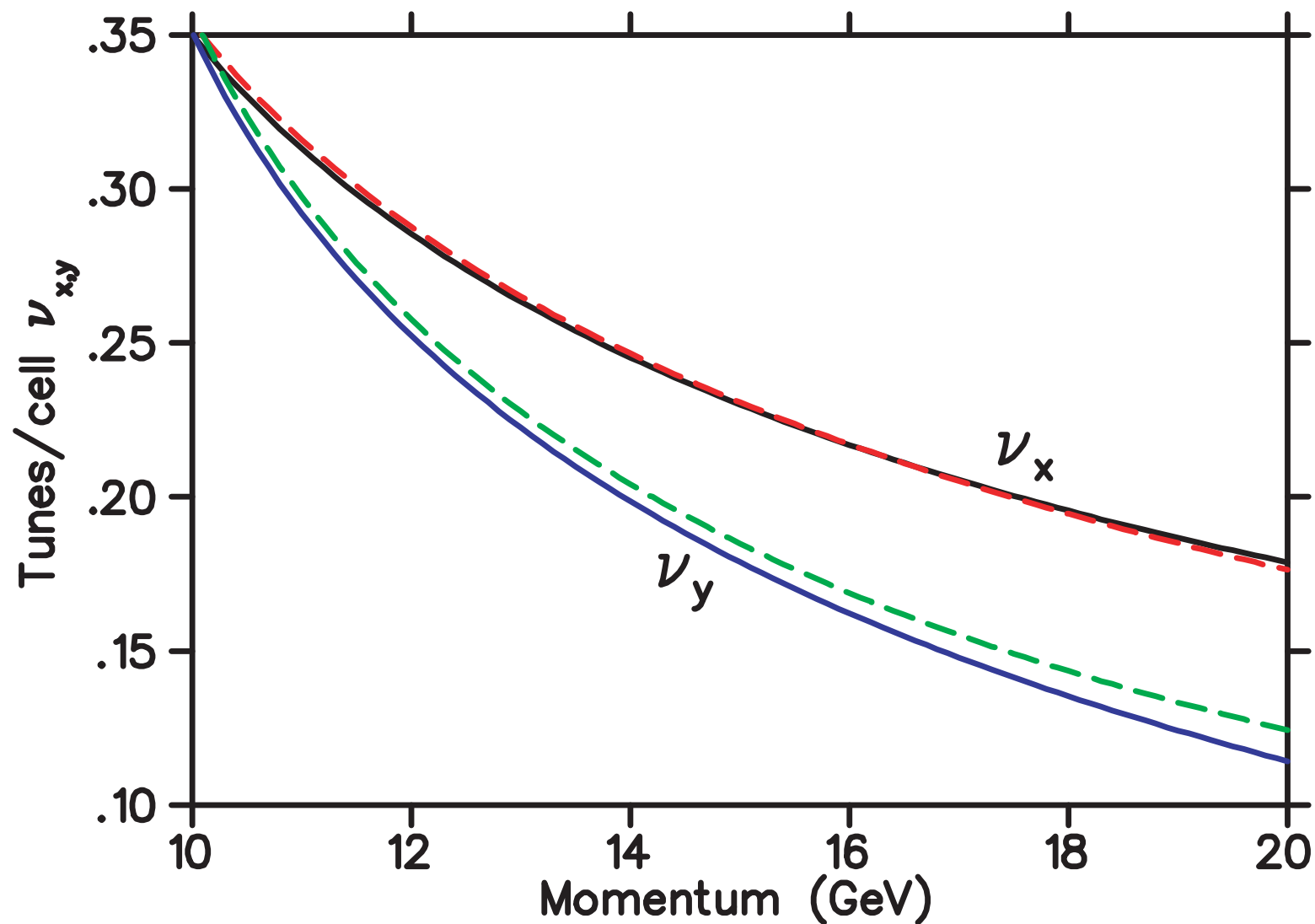


Cost Dependence on Acceptance



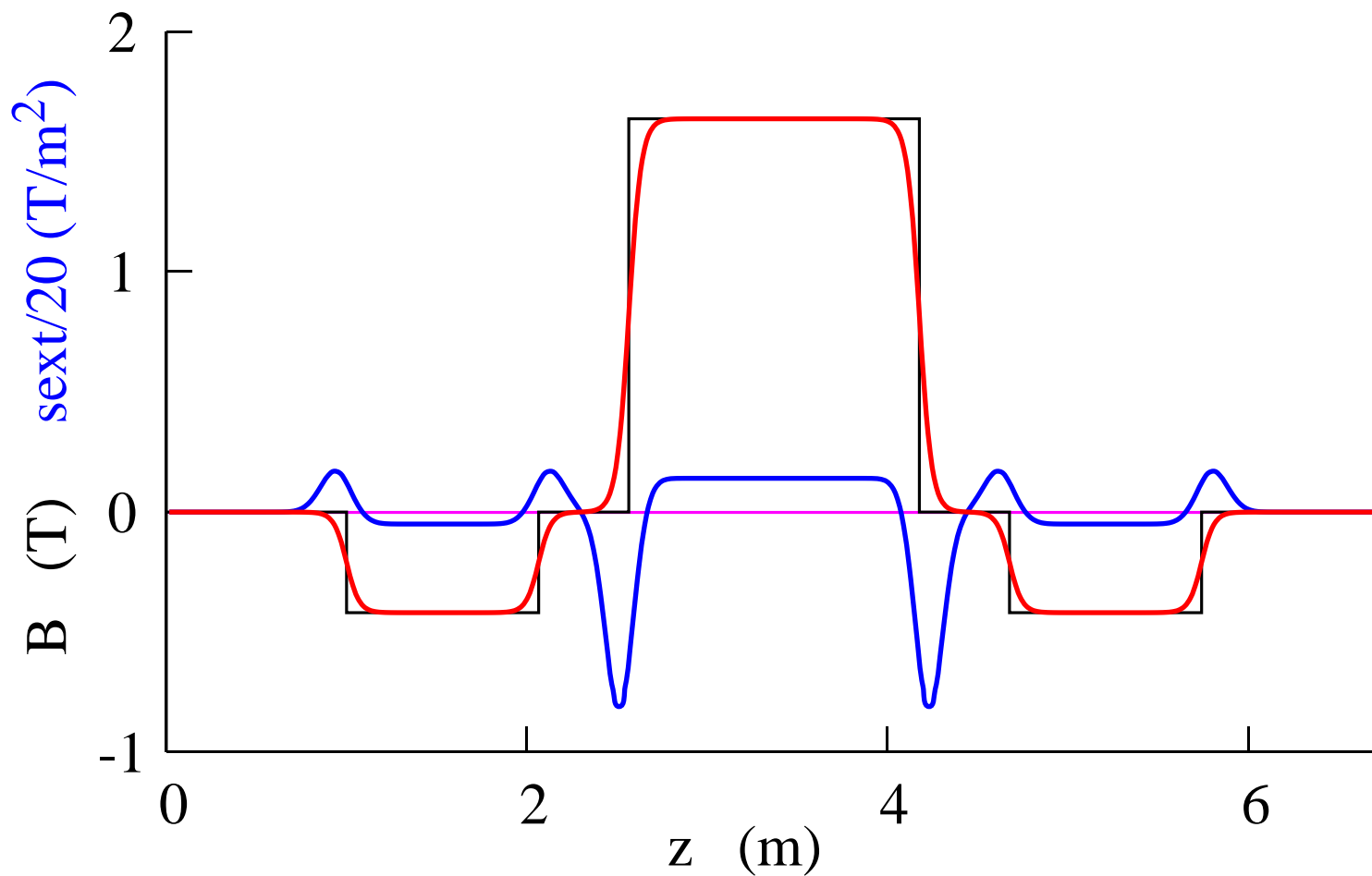
- Simplicity of lattice leads to desire for analytic treatment
 - ◆ Speed up above optimization process
 - ◆ Directly compute first-cut design
- Wide range of energy makes it more than a simple linear problem
- Thin lens models (Craddock, Koscielniak, Johnstone)
 - ◆ Produce simply expressed results: good for design
 - ◆ These have been used to produce parameter sets
 - ◆ Give a good picture of scaling laws
 - ◆ Not highly accurate, but not too bad
- Thick lens models (Koscielniak)
 - ◆ We know the solution for linear magnets
 - ★ But not exactly in the curved geometry
 - ◆ Can get highly accurate solutions, except for small rings
 - ◆ Don't lead to nice, easy to write down formulas

Accuracy of Thick-Lens Model

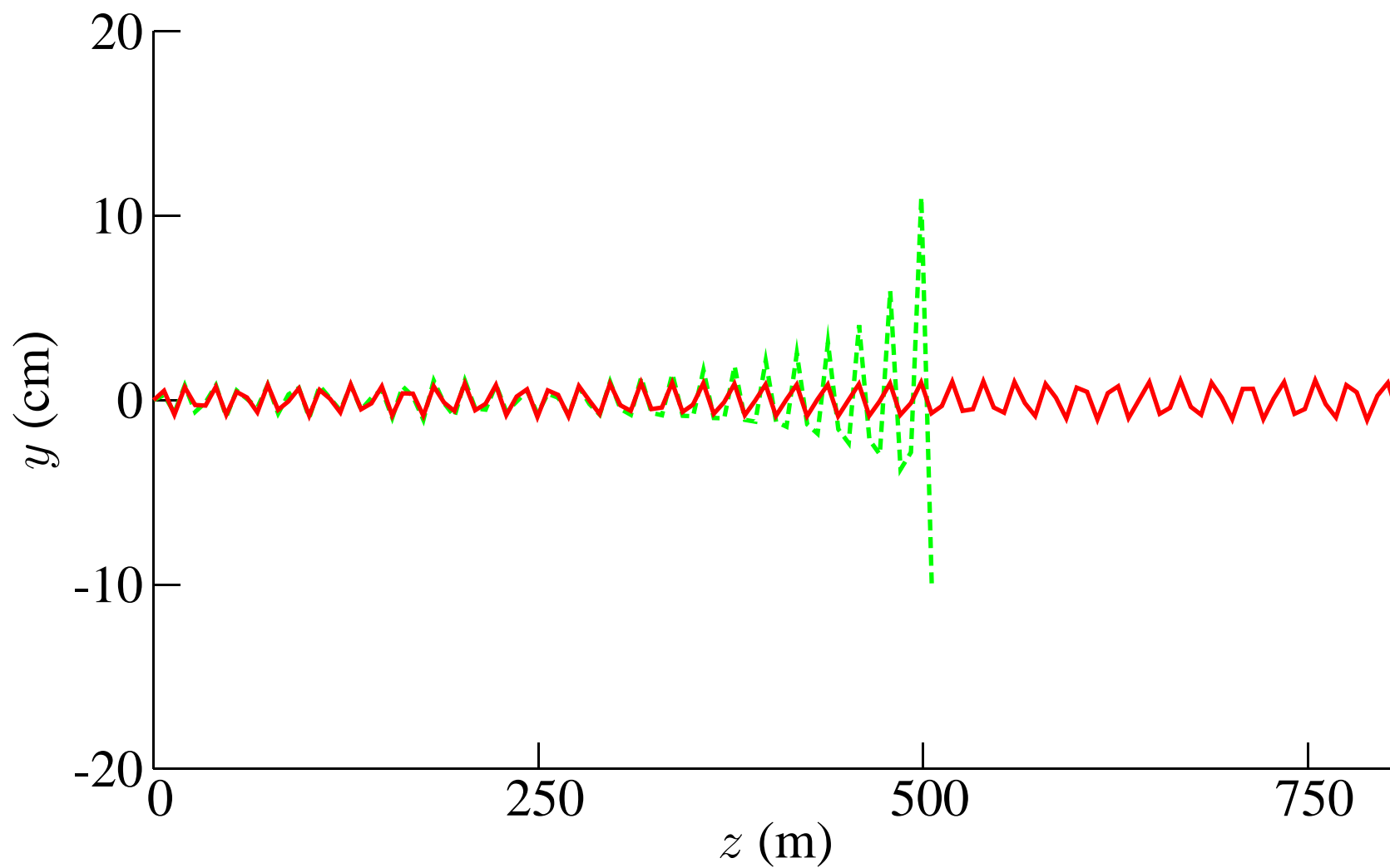


- FFAGs present challenges to tracking codes
 - ◆ Large energy range, often large dynamic aperture
 - ◆ Short magnets: end fields make significant contribution to dynamics
 - ★ Few tracking codes can handle complex ends
 - ★ COSY handles ends, but truncated power series sometimes fail to converge over desired range
 - ★ ICOOL (Fernow), ZGOUBI (Méot) both handle ends to some extent
- Tracking has begun on some lattices (Palmer)
 - ◆ Muon acceleration lattices
 - ★ Sextupole ends on magnets included
 - ★ Resonance crossing with end nonlinearities causes rapid beam loss
 - ★ Showed a fairly precise body sextupole correction fixes the problem

Tracking: Field Profile

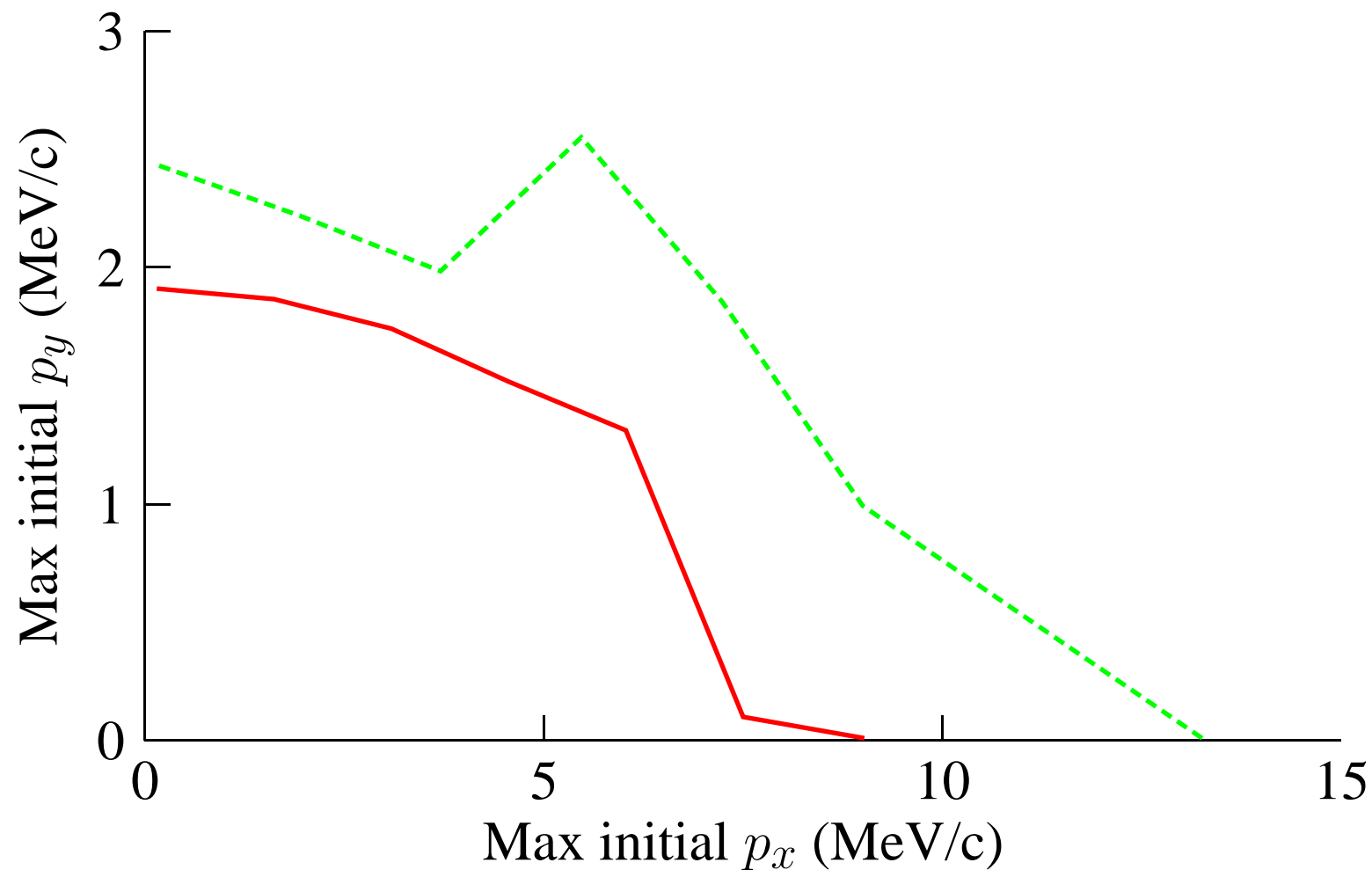


Tracking: Loss at Resonance

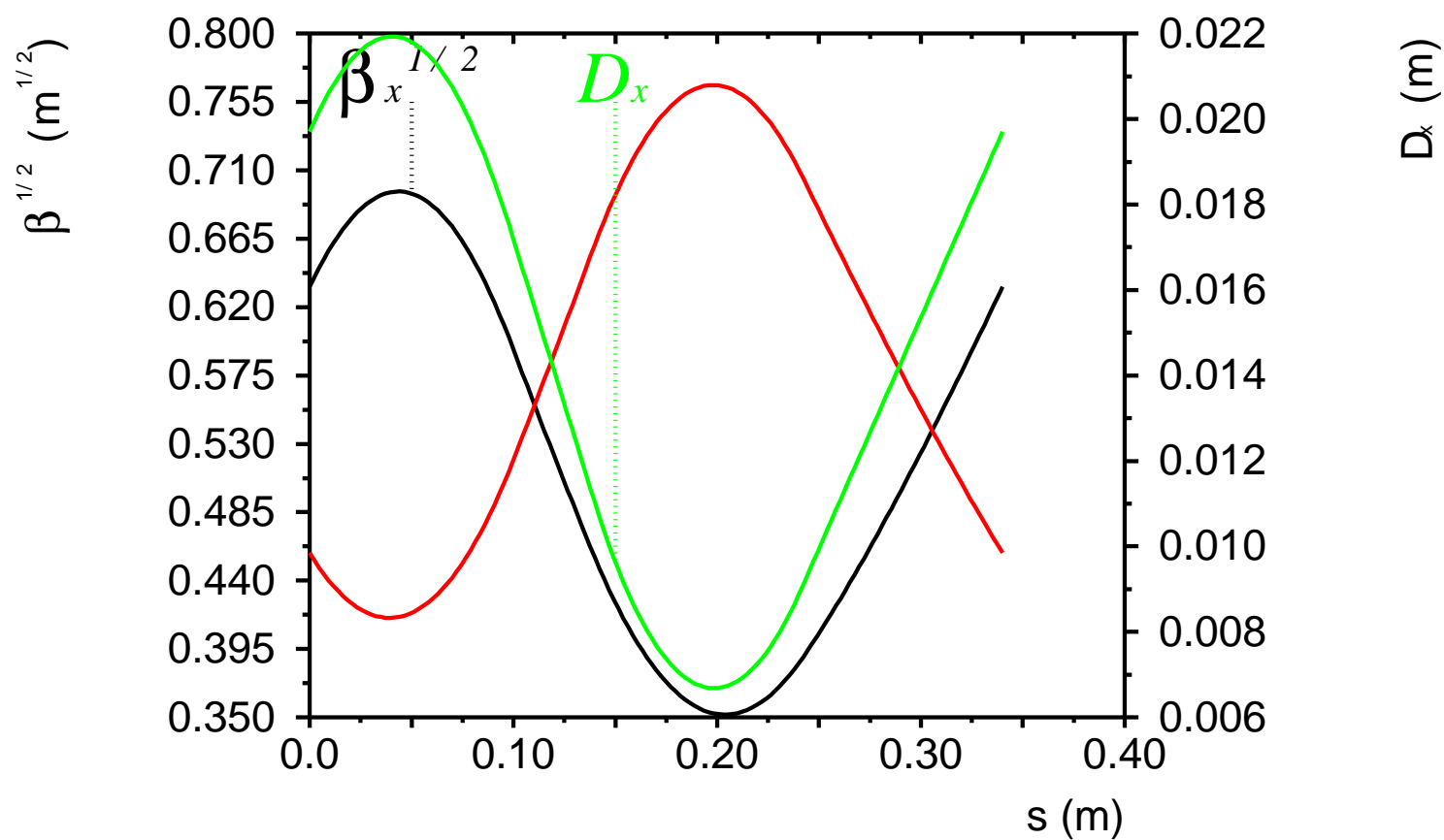
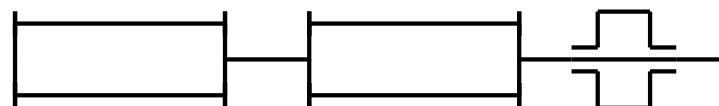


- Used ICOOL to track PRISM
- Dynamic aperture much higher for $y = 0$ than with slight vertical amplitude
- Tried multiple variations on the end profile; found a more slowly varying end profile gave better dynamic aperture
- Produced a linear non-scaling version of the PRISM lattice
- Appears to have a better dynamic aperture
 - ◆ Plot is somewhat deceptive: linear non-scaling is at 80 MeV/c, scaling is at 68 MeV/c

Tracking: PRISM Dynamic Aperture



- Would like to build low energy (10-20 MeV?) linear non-scaling FFAG
 - ◆ Linear non-scaling FFAGs are of great interest
 - ◆ Nobody has ever built one
 - ◆ Prove we understand the dynamics
 - ◆ In particular, demonstrate that we can accelerate in the unusual accelerating mode used for high-frequency RF with muons (Koscielniak's talk)
- Several authors have produced parameter sets
 - ◆ Typically S-band RF, a 10–20 m in circumference
- Keil and Sessler have analyzed a couple designs more thoroughly
 - ◆ Errors
 - ◆ Hardware considerations
- There is serious discussion of moving forward with a proposal, especially in Europe



- Much progress has been made recently in the design of non-scaling FFAGs
- Non-scaling FFAGs have been proposed for several new applications
- We are gaining a better understanding of how to optimally design these machines, particularly linear non-scaling FFAGs
 - ◆ Both analytic and numerical methods are being employed
 - ◆ These methods are leading to understanding of design principles
- Non-scaling lattices are being extended beyond the simple linear non-scaling lattices
- Serious consideration is begin given toward an electron model to demonstrate linear non-scaling FFAGs